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RADIATION PRODUCED BY THE MODULATED ELECTRON
BEAM OF A FREE ELECTRON LASER

By

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ABSTRACT

The electron beam in a free electron laser (FEL) becomes axially modulated at the optical wave length of the FEL radiation. This electron beam passed through a gas may produce intense Cerenkov radiation. The effects of the radial and axial dimension of the electron bunches on the radiation are explored.

I. Background

In several publications,[1,2] we have explored the coherent Cerenkov radiation produced by electron beam bunches in a dielectric medium, such as air. The radiation from a single electron is weak, yielding of the order of ten optical photons per meter in air. The beam bunches from an r.f. accelerator, with 10^{11} electrons per bunch, radiate coherently at low frequencies which allows radiation in the microwave range. The factor of 10^4 loss, occurring because the intensity is preportional to the frequency, is more than offset by the increase resulting from coherence. The coherent radiation tends to cancel at higher frequencies, in which the wavelength of the radiation is smaller than bunch size. The size is about 1 cm for the bunch from an S-band accelerator implying a maximum radiated frequency of about 30 G Hz.

II. Basic Formulation

The electron beam from a free electron laser (FEL) offers the possibility of observing and using coherent Cerenkov radiation at optical frequencies and their relatively high output power. The electron beam in the FEL, after interacting with the wiggler and radiation fields, must become modulated in the axial direction. This "wasted" electron beam, usually stiff because it is relativistic, could maintain its modulation, pass into a gas cell and produce coherent Cerenkov radiation. The resulting radiation could be used to diagnose the electron beam modulation. At higher currents the radiation intensity might be a significant

power source, although, breakdown of the gas would be a limitation. Hollow dielectric wave guides, successful for the microwaves[5], have not been used in the optical range, but could possibly be used to avoid problems associated with passing the beam directly through the dielectric medium.

III. Cerenkov Radiation from Charges and Charge Distributions

Frank and Tamm[6] deduced the power radiated by a charge moving at velocity v in a medium in which the radiation velocity is c, and v>c. The radiation velocity in free space is c_o and we let $\cos\theta_c = c/v$, where $c = (\mu\varepsilon)^{-1/2}$ and c_o is the free space value, the radiation is produced in a cone propagating at an angle θ_c with respect to v. The radiation has a continuous spectrum, and in the frequency range $d\omega$, the radiated power for an infinite path length is

$$P(\omega)d\omega = \frac{\mu V}{4\pi} q^2 \sin^2\theta_c \;\omega d\omega\; F^2(\vec{k}), \tag{1}$$

where

$$F(\vec{k}) = q^{-1}\iiint e^{i\vec{k}\cdot\vec{r}} \rho_o(\vec{r})dv, \tag{2}$$

and $\rho_o(\vec{r})$ is the charge density evaluated in the lab coordinate system at t=o. The vector $\vec{k}$ is in the direction of the emitted radiation and $k = \omega/c$. $F(\vec{k})$ may be called the form factor of the charge distribution, and it is normalized to be unity in the limit $\vec{k} = o$. For a point charge $F(\vec{k})$ is identically one for all values of $\vec{k}$. The actual forms of Eq.1 and 2 are those given in Ref.1,2 and reduce to the Frank and Tamm results if F = 1.

For a periodic series of charge bunches, the corresponding derivation predicts radiation appearing at harmonics ω of the bunch angular frequency ω_o, with the power given by

$$P(\omega) = \frac{\mu V}{4\pi} \omega\omega_o \sin^2\theta_c F^2(\vec{k})q^2 \quad (3)$$

for an infinite path length. Here q and $P(\omega)$ are the charge and the power radiated per bunch. $F(\vec{k})$ is still defined by Eq.2, and in this periodic case, the integration is carried out over a single bunch. Eq.3 is derived by completely classical reasoning and has been confirmed[1,7] for radiation in the microwave range for bunch sizes about 1 cm in length and emitted radiation up to 30 GHz. In the optical range where quantum effects might be expected, Eq.1 is satisfied for point charges (with F=1). We assume that the Eq.3 holds in the optical range. The charge distribution must be specified to proceed. Let $s^2=x^2+y^2$ and

$$\rho_o(\vec{r}) = \rho_r(\vec{s}) \rho_L(z) \quad (4)$$

With this form for $\rho_o(r)$, the form factor becomes

$$F(\vec{k}) = F_r(\vec{k}_s) F_z(k_z) \quad (5)$$

The charge per bunch, q is

$$q = I \ell/v \quad (6)$$

where I is the current, ℓ is the spacing between bunches, v is the bunch speed.

Letting N be the harmonic number, the power radiated per bunch is

$$P(\omega) = \pi\mu N v \sin^2\theta_c \; I^2F^2 \tag{7}$$

which depends on the current in the bunch, not on the total charge. Also, the radiation is more efficient for large N if the form factor F allows such high harmonics. Finally, the efficiency increases with I, because the beam power is proportional to I but the radiated power varies as I^2. To consider the efficiency for radiation further, Eq.7 may be manipulated. The energy radiated per unit length by one bunch is P/v, while the energy required to form the bunch is qV or $I\ell V/v$, where V is the accelerating voltage in Volts. If the radiating medium is of length L, we may form the dimensionless ratio E(radiated)/E(beam) which from Eq.6 become

$$E(rad)/E(beam) = \pi \; N \; Z_o \frac{I}{V} \; \frac{L}{\ell} \cos\theta_c \; \sin^2\theta_c \; F^2 \tag{8}$$

wnere Z_o is the impedence of the medium, i.e., $Z_o = (\mu/\varepsilon)^{1/2}$. Let $I=10^2$A, $V=10^8$ Volts, $\sin\theta_c=10^{-2}$, F=1, L=1 m and $\ell=10^{-6}$m. Then E(rad)/E(beam) is about 10%. Thus fairly high efficiency for

radiation may be achieved for possible values of L/ℓ, and extremely high efficiency could occur if ℓ, the beam period, is in the optical region, as realized in a free electron laser. The main problem is the small value of F which results for a wide beam.

IV. Specific Considerations for an FEL Beam.

The Equations developed (Eq.7,8) describe the radiation by a periodic electron beam. The main problem comes from the form factor F which describes the charge distribution. For an FEL, the axial charge distribution is modulated at the optical wave length, of the order of microns, but the radial beam dimensions may be as large as millimeters. Then F, which describes diffraction, may be very small. To proceed, we consider a modulated beam, in which $\rho_L(z)$ in Eq.4 is given by a cosine function, which restricts harmonic production to N = 1. Thus,

$$\rho_L(z) = 1 + A\cos(Kz) \tag{9}$$

We may let $\rho_r(s)$ be axially symmetric, in the form of a uniform disc of radius r, or a gaussian in the form of $\exp(-s^2/a^2)$. For either case, Eq.9 yields

$$F_z(k_z) = \delta_{k_z,o} + \frac{A}{2}\delta_{k_z,K} + \frac{A}{2}\delta_{k_z,-K} \tag{10}$$

From the general considerations of Ref.1,2, the vector $\vec{k}$ is at an angle θ_c to the beam axis, the radiation at any frequency

stays in phase with the electron bunch, and $k_s = k \sin \theta_c$. From Eq.10 with $k_z = K$, the radiation matches the periodicity of the electron beam, and higher harmonics in Eq.9 would give $k_z = NK$. Note that because $\omega = ck$ for the radiation and $\omega_o = vK$ for the beam, and $k_z = k \cos \theta_c$ we have, setting $k_z = NK$, $\cos \theta_c = c/v$ gives $\omega = N\omega_o$. This means that the Cerenkov radiation, in the medium with velocity c, has the same frequency as the FEL radiation in vacuum, or an integer multiple thereof.

For the disc of radius r,

$$F_r(k_s) = 2J_1(k_s r)/k_s r \ . \tag{11}$$

For the gaussion radial distribution,

$$F_r(k_s) = e^{-k_s^2 a^2/4} \ . \tag{12}$$

Both form factors arise from a non-zero radial distribution of charge, and both yield a great suppression of radiation from diffraction from a finite source when the radius parameter (r or a) is many times larger than the wave length of the radiation. If the beam radius parameters in Eq.11 and 12 are 10^{-3}m, the radiation has $\lambda = 10^{-6}$ m and $\theta_c = 1.3^o$ for air, and is very small for the gaussian, because $\ln F_r^2 = -5.09\times10^3$. For the disc, $k_s r = 141.5$ and $F_r^2 = 8.79\times10^{-7}$ if the envelope of the oscillating function of Eq.11 is considered.

To conclude this section, we substitute the results of Eq.9, 10 into Eq.7 to obtain the power radiated per (optical) bunch of the electron beam

$$P(\omega) = \frac{\pi\mu}{4} Nv \sin \theta_c I^2 A^2 F_r^2(\vec{k}_s) \qquad (13)$$

In this form the parameter A describes the axial modulation of the charge according to Eq.9. If harmonics other than N=1 are considered, Eq.9 becomes a Fourier series and depends on N.

V. Enhancement of FEL Cerenkov Radiation

The previous section shows that the FEL electron beam, because of its short axial modulation length is potentially an efficient radiator but a wide radial dimension may severely limit the radiation, by diffraction. Eq.11, 12 are identical to optical diffraction by uniform and gaussian shaded apertures, but the Cerenkov condition requires the vector $\vec{k}$ to be on the Cerenkov cone, which picks out a narrow ring far out on the circular diffraction pattern. The radiation could be increased by at least three methods (a) concentration of the same current into a smaller radius, (b) passing the beam through an aperture, which would decrease the current but increase the form factor, and (c) bending the beam in a magnet. The last two are considered in more detail below

A. Radiation Enhancement - Aperture

Let the beam pass through an aperture of small radius r′ The gaussian beam then becomes a uniform disc with a form factor

given by Eq.11 with r' replacing r. Using the envelope form $2J_1(x)/x \rightarrow (8/\pi x^3)^{1/2}$,

$$\frac{P_A}{P} = \frac{8}{\pi(k_s r')^3} \frac{(r')^4}{a^4} e^{+k_s^2 a^2/4} \tag{14}$$

where P_A and P are the powers with and without the aperture. The power increase may be very large, but only because the gaussian originally caused strong suppression.

For the disc beam, the result is

$$\frac{P_A}{P} = \frac{r'}{r} \tag{15}$$

There is a loss of power for the disc, because the square of the form factor is proportional to $(r')^{-3}$ but q^2 varies as $(r')^4$

B. Radiation Enhancement-Deflected Beam

Let the beam velocity be deflected by an angle θ_c by a magnet. The planes of the charge discs will be unchanged so that the normal to the disc will be at an angle θ_c to the velocity. Part of the Cerenkov cone will then be perpendicular to the disc with no diffraction. Let ϕ be the azimuth angle of $\vec{k}$ in the Cerenkov cone, relative to the direction in which $\vec{k}$ is perpendicular to the disc. As the direction of $\vec{k}$ changes, the first diffraction null occurs for

$$\frac{|\Delta\vec{k}|}{|\vec{k}|} = 1.22 \frac{\lambda}{2r} \tag{16}$$

The fraction f of the Cerenkov cone within this first diffraction lobe is then approximately

$$f = \frac{|\Delta\vec{k}|}{2\pi k_s} = \frac{1.22}{2\pi} \frac{\lambda}{2r} \frac{1}{\sin \theta_c} \tag{17}$$

For the given λ, r and θ_c, $f = 4.28 \times 10^{-3}$.

The effect is that this small fraction f of the cone produces radiation, which is relatively strong, with $F_r^2 = 1$ in this region, as opposed to $F_r^2 = 8.79 \times 10^{-7}$ for all the cone of the undeflected beam. Thus the power output is enhanced greatly over the diffraction-suppressed radiation without the magnetic deflection.

VI. Summary

The modulated beam from an FEL will produce Cerenkov radiation if it passes through air, if the energy is above threshold. This radiation is potentially very strong, because the electron bunches radiate coherently and the efficiency increases with frequency. Realistic beams pose a problem because the relatively large radial dimensions result in diffractive suppression of the radiation. In the text, two methods are considered to alleviate the diffraction loss-passing the beam through an aperature, and bending it in a magnetic field. The latter method seems more promising for the assumed beam parameters.

These calculations are based on classical electrodynamics. The results are verified in the usual point particle Cerenkov effect in the optical range, and coherent emission by beam bunches in the microwave range. But here, a new process is explored-coherent Cerenkov emission but in the optical range. Experiments should be done, to explore the physics in this range, as well as provide diagnostics for FEL beams.

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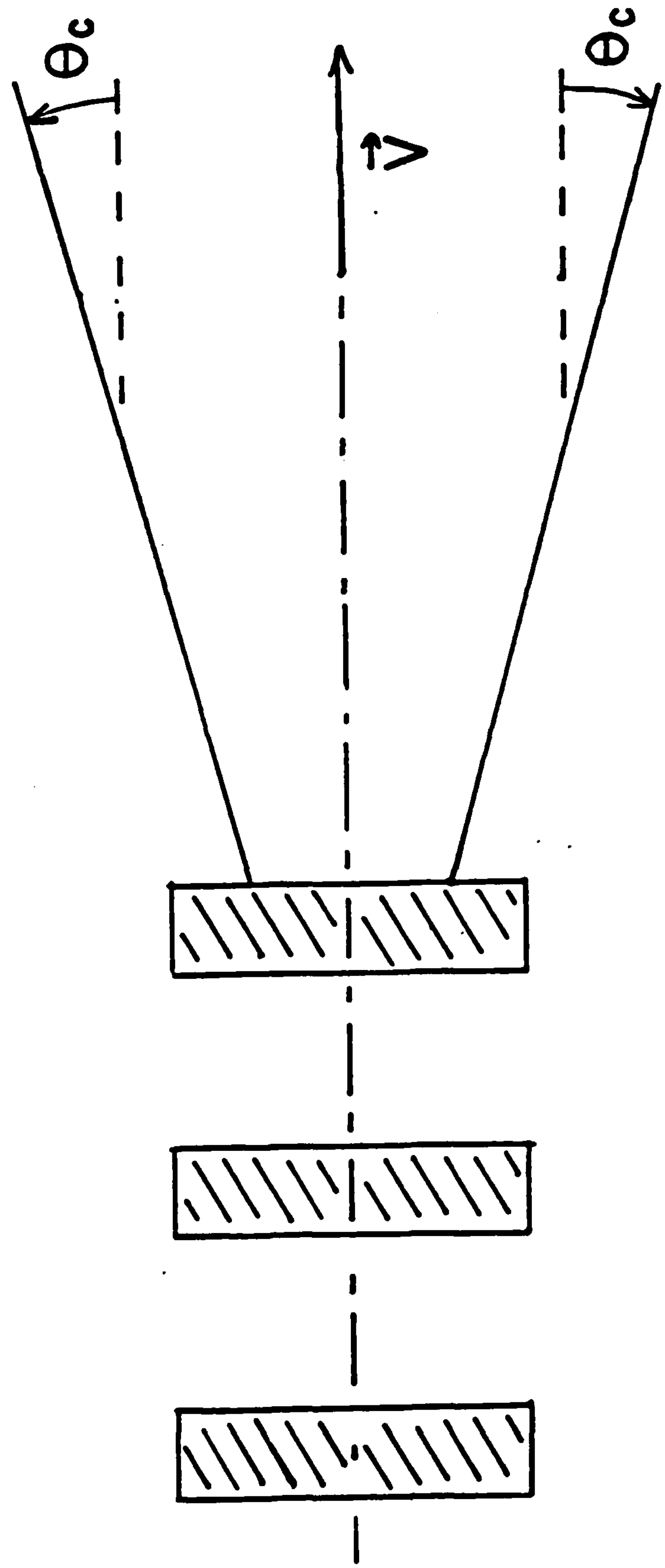
Figure 1. The modulated bunches produce Cerenkov radiation, but a relatively large radius produces diffraction losses.

Figure 2. The charge bunches are bent in a magnetic field, which changes the direction of $\vec{v}$ but leaves the plane of the disc unchanged.

Figure 3. The ray shown by $\vec{k}$ is on the Cerenkov cone and normal to the disc, so radiation is strong. This strength will persist out to an angle θ such that diffraction produces a null. Thus part of the Cerenkov cone produces strong radiation.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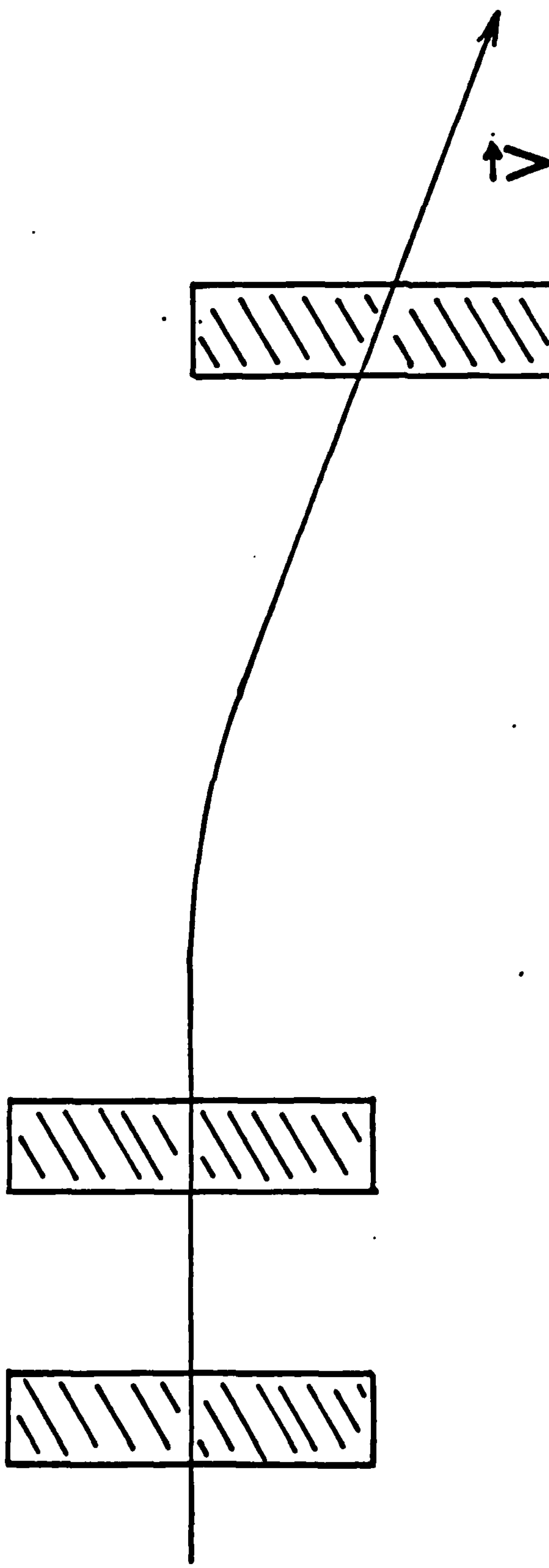

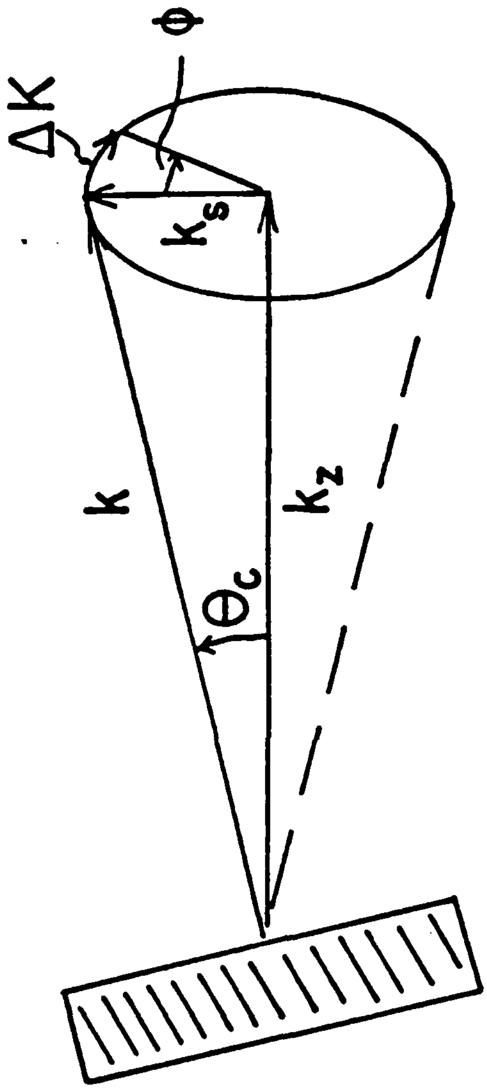
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